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Exergo-environmental analysis of nano fluid ORC low-grade waste heat recovery for hybrid trigeneration system

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Abstract

In this work, a thermodynamic model based on theoretical and experimental data is developed for utilizing nano fluid organic Rankine cycle (nORC) in a trigeneration hybrid system. The trigeneration hybrid system composed of a solid biomass boiler, gas turbine cycle, a nORC, cooling, and a heating system. The exergy of the system analyzed; moreover, environmental impact assessments and interrelated parametric studies are examined. The results show higher exergy efficiency for the hybrid trigeneration employed nORC, and indicate that carbon dioxide emissions for utilizing nano fluid in nORC trigeneration system are less than conventional working fluid system.

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Keywords:

1. Introduction

The potential for using hybrid trigeneration energy systems utilizing low-grade hear recovery for electricity, heating, and cooling generation is big and growing [1]. The trigeneration system is aiming to increase the overall thermal performance as well as reduction of greenhouse gas emissions, essentially utilizing the existing waste energy [2]. In terms of the conversion of low grade heat to electricity, recent researches focused on the organic Rankine cycle (ORC) [3]. However, one of the most important issues in ORC hybrid system is the size of ORC components and limitation on heat transfer coefficients in the temperature range of utilized heat sources [4]. This has motivated researchers to investigate different working fluids and improved configurations of such systems [5].

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Nomenclature

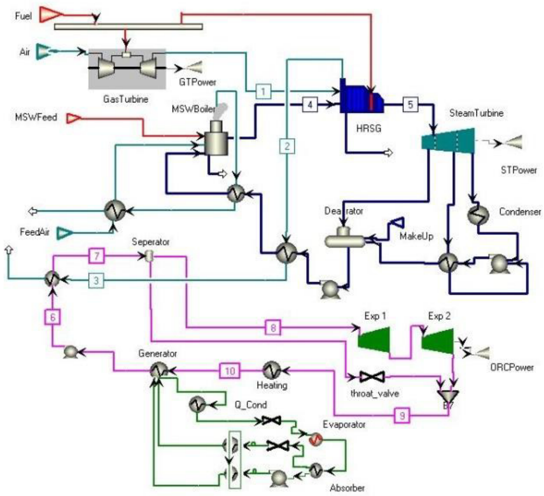
$\dot{E}x$	exergy flow rate (kW)
$\dot{E}x_n$	exergy destruction rate (kW)
Greek symbols	
η	energy efficiency
η_{exergy}	exergy efficiency

In a nano fluid organic Rankine cycle (nORC), compared to a conventional ORC, nano particles in organic based fluid is involved [5]. The addition of nanoparticle enhances heat transfer properties of the base working fluid [6].

In the present study, the performance of a hybrid trigeneration plant combined with nORC is optimized by a component wise simulation Aspen Plus software. Exergy analysis combined with environmental assessment is developed with help of introducing enthalpy and entropy functions; in addition, a detailed break-up of energy and exergy destructions and losses for the considered plant is presented.

2. Modeling

The Fig 1 shows model of the studied novel cycle in Aspen Plus. The model consists of hybrid gas turbine combined cycle as a topping cycle. Fuel is injected into the combustion chamber and hot gas pass through a gas turbine (GT) (high temperature); the expanded gas after the GT enters the heat recovery steam generator (HSRG) to superheat the low quality steam coming from solid biomass boiler and sending to the steam turbine (medium temperature). The waste heat of the flue gas existing from HSRG is a prime mover of the evaporator in nORC trigeneration cycle to produce power, heating, and cooling by absorption chiller. Working fluid of the nORC is silver nano pentane (10 nm, 0.5% W/V). Further details about working fluid and nORC are given in references [5,7].



Point number	Specification
1	hot gas exiting gas turbine
2	hot gas exiting HSRG
3	flue gas entering the nORC evaporator
4	low pressure steam from MSW boiler entering HSRG
5	high pressure steam entering steam turbine
6	saturated nORC liquid working fluid leaving the generator
7	vapour leaving the nORC evaporator
8	vapour entering the nORC expander 1 and expander 2
9	nORC working fluid entering the heating part of trigeneration
10	nORC working fluid entering the generator

Fig 1 Graphical representation of the Aspen Plus hybrid nORC trigeneration system model

In order to calculate the thermophysical properties of nano organic fluid and exergy analysis of the system, some subroutines are developed, as well as experimental data are integrated into the model. Some assumptions are made to render the studies more traceable and illustrate the principle points:

- All processes are considered at steady state.
- Pinch point temperatures are considered 7°C to 10 °C, and the dead state is 1 bar and 20 °C.

3. Exergy analysis

The exergy balance over each component from the first and second law of thermodynamics can be calculated with using Eq. (1) [8] . Where subscripts e and i represent inlet and outlet respectively, and $\dot{E}x_D$ is the exergy destruction. The parameter exergy of heat transfer and work are $\dot{E}x_Q$ and $\dot{E}x_w$.

$$\dot{E}x_Q + \sum \dot{m}_i\, ex_i = \sum \dot{m}_e\, ex_e + \dot{E}x_w + \dot{E}x_D \qquad (1)$$

Evaluation of the flue gas exergy is based on the exergy ratio ($\xi = ex_f / LHV_f$), where methane uses as a fuel is simplified to $\xi_{CH4} = 1.06$.

4. Exergy efficiency

The exergy efficiency is defined as the product exergy output divided by the exergy input. In this study expressed as Eq. (2).

$$\eta_{exergu,trigeneration} = (\dot{W}_{net,GT} + \dot{W}_{net,ORC} + \dot{E}x_{Q,heating} + \dot{E}x_{Q,cooling}) \big/ \dot{E}x_{fuel} \qquad (2)$$

5. Exergo-environmental analysis

The major goal of present study is to consider the environmental impacts as producing the CO and NOx. Sayyaadi [9] determined the pollutant emission in grams per kilogram of fuel for gas turbine combustion chamber based on adiabatic flame temperature in Eq. (3) and Eq. (4) , where τ is the residence time in the combustion zone and equal to 0.002 [10]:

$$m_{NO_x} = (0.15E16\tau^{0.5}\exp(-71100/T_{primary\_zone}) \big/ (P^{0.05}_{combustor,inlet}(\Delta P_{combustion,chamber}/P_{combustion,inlet})^{0.5}) \qquad (3)$$

$$m_{co} = (0.179E6\exp(7800/T_{primary\_zone}) \big/ (P^{2}_{combustor,inlet}\tau(\Delta P_{combustion,chamber}/P_{combustion,inlet})^{0.5}) \qquad (4)$$

The environmental advantage of using municipal waste (MSW) boiler is the avoided CH4 credit. In this study, MSW considered 75 percent carbon-neutral and with LHV equal to 11.4 MJ/Kg.

6. Results and discussion

The exergy analysis (Fig 2(a)) results display that the exergy destruction in the combustion chamber is higher than in other components, mostly due to the irreversibility associated with combustion. Moreover, it exhibits that the absorption cycle does not show significant energy destructions because of utilizing waste heat. However, the exergy destruction in nORC case is 30% lower than ORC, mainly due to higher heat transfer coefficient of silver nano pentane in comparison with pentane in evaporator and condenser.

It can be seen from Fig 2(b) that the nORC hybrid trigeneration cycle has about 14% less CO2 emissions than the ORC hybrid trigeneration cycle. In addition, the graph shows that the exergy efficiency in nORC hybrid trigeneration cycle is around 12% more than ORC hybrid trigeneration cycle. The Fig 2(c) shows exergy efficiencies for different hybrid cycles with different GT inlet temperatures. It is shown that the exergy efficiency for nORC is almost higher than the ORC hybrid trigeneration, and increases with increasing GT inlet temperature.

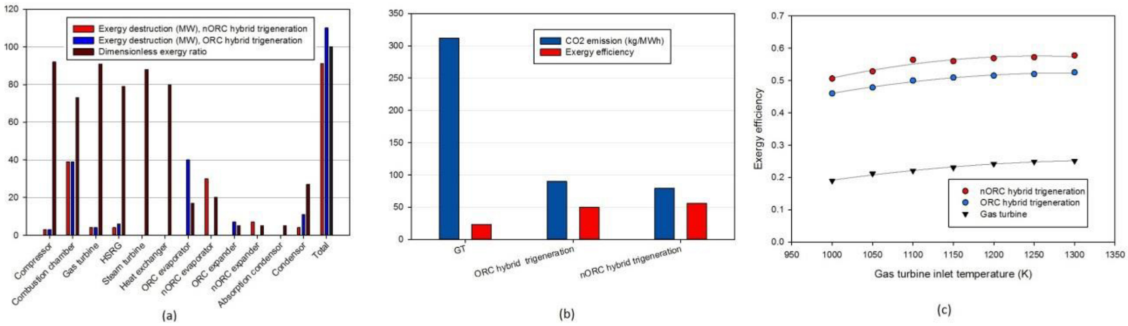


Fig 2 in both ORC and nORC with the same heat source (a) Exergy destruction rate and dimensionless exergy efficiency for each components (b) Comparison of exergy efficiency and environmental impact of different hybrid systems (c) Variation of gas turbine

Conclusions

The model and exergo-envirnmental analysis of hybrid nORC trigeneration system has been studied. The results show that utilizing nORC in hybrid systems in comparison with ORC, with the same heat source, has higher exergy efficiency, less exergy destruction, and less CO2 emissions.

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